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REVIEW

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Tropical cyclone warning and forecasting system in Bangladesh: challenges, prospects, and future direction to adopt artificial intelligence

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Abstract

Bangladesh is a disaster-prone area due to its geographic location, especially since it is affected by a tropical cyclone (TC) almost every year. TC causes severe damage to lives and livelihoods in this region of Bangladesh. TC prediction and monitoring are still based on the traditional statistical model. In general, the conventional statistical model has the limitation of not handling nonlinear datasets in a precious way. However, the country is gradually adopting modern technologies like artificial intelligence (AI), machine learning (ML), and Fourth Industrial Revolution (IR4) technology for disaster management. The purpose of this study is to identify the scope of adopting new technologies like machine learning and deep learning (DL) for cyclone prediction in countries like Bangladesh, which are cyclone-prone but have constraints on funds to invest in this field. To establish the idea, we examine the research work on the TC forecasting model used in the country from 2010 to 2022. This paper examines the TC forecasting model used to identify the scope of improvement in the current system based on AI and process a better cyclone prediction system using an AI-based model. This study intends to reveal the gaps in mainstream cyclone prediction methods and focus on cyclone prediction system improvement. Moreover, this work will summarize the current state of the TC prediction forecasting system in Bangladesh and how the incorporation of modern technology can increase its efficiency. Finally, as a final note, we conclude this paper with the answer of proximity to the proposal of including AI in cyclone detection and prediction systems. A workflow diagram to address cyclone prediction based on ML and DL has also been presented in this paper, which may augment the capacity of the Bangladesh Meteorological Department (BMD) in performing their responsibility. Moreover, some specific recommendations have been proposed to improve the cyclone prediction system in Bangladesh.

Keywords Cyclone Prediction, Artificial Intelligence, Disaster Management, Accurate Tropical Cyclone Forecasting, Machine Learning Model

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1 Introduction

Warm equatorial ocean waters are the source of cyclone formation. Rising temperatures and moisture at the sea surface produce a low-pressure area that facilitates the formation of tropical storms (TC). Changes in these ar- eas indicate fluctuations in the cyclone's intensity. The tranquil"eye" in the cyclone's core is encircled by the dangerous"eyewall" that has the highest winds and most rainfall. Additionally,"rain bands," linked to cloud

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structure and precipitation, bring extensive rainfall. Exploring these features, including the eye, eyewall, and rain bands, is essential for comprehending the behavior and structure of tropical cyclones (Debsarma 2009).

Very few countries in the world have observed the atrocity of TC. In general, countries that are geographically located in tropical and subtropical regions have to face the outrage of TCs based on the pre-monsoon (March–May) and post-monsoon (October–December) seasons every year. Bangladesh is geographically located in the northern Bay of Bengal, one of the terrifying cyclone impact zones. Every year, nearly 5% of the total TC taking place worldwide occurs over the Bay of Bengal, and casualties in this area account for 80% of all TC casualties (Debsarma 2009). The key factors that induce TCs to form on a large scale along the coast of Bangladesh are the long continental shelf, shallow bathymetry, northward converging shape of the bay, the complex coastal layout including offshore islands, high sediment accretion rates, high astronomical tides, and the long tidal range between the east and west coasts (Chowdhury 1993; Mohit 2018). However, Bangladesh has faced various natural hazards due to its geographical location and characteristics. multiplicity of rivers, etc. (The macroeconomic consequences of disasters 2009). Being one of the most densely populated countries (with 200 million people living within 144000 sq. km.), any natural disaster (Debsarma 2009) can lead to a great toll on human lives. Natural hazards like Cyclones and floods are some of the major disasters in this country that have caused damage to property in recent years. Bangladesh's 700-km coastline is the major active area for the development of TCs. From 1970 to 2007, cyclones caused more than 700,000 deaths. Cyclone Amphan (May 2020), Cyclone Aila (May 2009), Cyclone Sidr (November 2007), and Tropical Cyclone O2B (April 1991) are the major disasters (Noy 2016). These statistics make it a strong point for the adaptation of modern technology as well as the requirements to investigate the current cyclone scenario. In this paper, we intend to address those issues.

The existing development of cyclone management in Bangladesh mainly focuses on infrastructure development, engagement of trained volunteers, circulating TC forecasts, and warning system development. Infrastructure development mainly focuses on increasing the number of cyclone shelters in the vicinity of the cyclone-affected area. Trained manpower helps the res- cue operator after the cyclone. Last but not least, the development of an early warning system is a work in progress. The BMD has developed a Cy- clone Warning System (CWS) (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015) with the approval of the Government of Bangladesh. It circulates alert signals of the approaching cyclone through radio, television, and other mass media platforms. The existing system includes the following features: a) Position of the storm center, b) direction and rate of movement, c) area likely to be affected, specifying upazilas (administrative units in Bangladesh) of the district, if possible; d) approximate time of commencement of gale winds (speed more than 32 km/h or 52 km/h), e) maximum wind speed expected, f) Approximate height of the storm surge or tide and areas likely to be affected. However, the existing CWS system is not very accurate and reliable and is not trusted by the local people.

In recent years, information technology has played an important role in disaster management (Economic modeling for disaster impact analysis: Past, present, & future 2007). Having A good warning system for any disaster with a good prediction method helps to reduce the damage. Recently, DL and ML-based approaches have been applied not only to detect the cyclone but also to identify the change in its path along with its intensity (Chowdhury 1993). Although ML-based approaches have been used in meteorological data for quite some time; specific use In cyclones, prediction is very limited. Notable work on cyclone prediction can be found in Debsarma (2009); Mohit 2018). In (Debsarma 2009), a DL-based approach has been proposed to predict cyclones by identifying the cyclone eye, which also helps to understand the intensity development and TC track prediction as time series forecasting of TCs. These works are very promising and have a significant impact on cyclone prediction. However, adopting this technology in a real-life environment or practically is still very challenging.

In this work, we intend to identify the scope of cyclone prediction from Bangladesh's perspective, which leads us to review all the research papers in the context of TC prediction and warning systems from the perspective of Bangladesh. However, this study also involves an onsite investigation of the current cyclone observation scenario in Bangladesh. We tried to analyze.

Those works in terms of the forecasting process and warning systems that prevailed in Bangladesh. In addition, we have suggested an AI-based architecture for a cyclone prediction system. The novelty of the paper can be narrated as follows:

- An extensive study has been carried out on all the available literature in the domain of cyclone prediction and warning systems to understand the current forecasting scenarios, especially on the early warning system. To the best of our knowledge, no prior study of this kind has been conducted before.
- Potential field has been identified to adopt new technologies like ML and DL for cyclone prediction in Bangladesh and the countries alike. We think this

type of identification will assist the Government in determining which areas need improvement in the adoption of 4IR.
- A novel framework has been proposed to implement the cyclone pre- diction system using AI.
- Some future directions and proposals such as GAN-based data augmentation, machine learning in forecast validations, and handling successive cyclone events have been discussed based on the current study. Such discussion has not been listed before and the meteorologist will benefit from this conversation in choosing the appropriate AI-based technology.

The rest of the paper is organized as follows. Tropical Cyclone (TC) life cycle describes the TC life cycle, and Cyclone warning system in Bangladesh provides us with insights into the cyclone warning system in Bangladesh and manifests the core idea of the cyclone prediction technique. Research gap delves into the conceptualization of the problem statement in our research paper. Followed by Literature review outlines the proposed AI-based model designed to address the current issue. In conclusion, Research gap encapsulates the key findings and insights derived from our exploration, providing a comprehensive wrap-up to this research work and drawing conclusive remarks.

2 Tropical Cyclone (TC) life cycle

A TC has a wheel of life starting from its genesis to landfall. In the meantime, it passes through several phases alongside its formation to dissipation.

The study of formation is direly needed for a meteorologist to estimate the track and intensity of a cyclone in the first place. A tropical cyclone matures after going through several developmental stages as a circulation system. This weather phenomenon starts life as a tropical disturbance, which usually appears when loosely structured cumulonimbus clouds inside an easterly wave show the first signs of a feeble circulation. The system becomes a tropical depression as it moves forward, reaching a wind speed of 36 km/h (23 miles per hour). Moving forward, if the circulation becomes more intense and wind speeds exceed 63 km/h (39 miles per hour), the system becomes a tropical storm. This change culminates in the storm being classified as a developed tropical cyclone when the maximum wind speed reaches 119 km/h (74 miles per hour) (https://www.britannica.com/science/tropical-cyclone).

2.1 Formation

Warm ocean waters and low wind shear areas act as primary trigger points to form a cyclone. Warm and moist air from the sea surface rise above creating a hollow space and causing turbulence to create with the air from different directions. Typically, an intense TC may sustain a speed of 119 km per hour with gusts of 320 km per hour. Figure 1 demonstrates the birth cycle of a TC. Heat and water vapor from the warm ocean are transferred to the air above, mostly through evaporation from the sea surface, which fuels tropical cyclones. The warm, humid air rises, expands, cools, and soon becomes saturated, releasing latent heat as water vapor condenses. This action warms and moisturizes the column of air in the developing disturbance's core. The rising air becomes buoyant due to the temperature differential between the warmer, rising air and the cooler surroundings, intensifying its upward motion (Gray 1998).

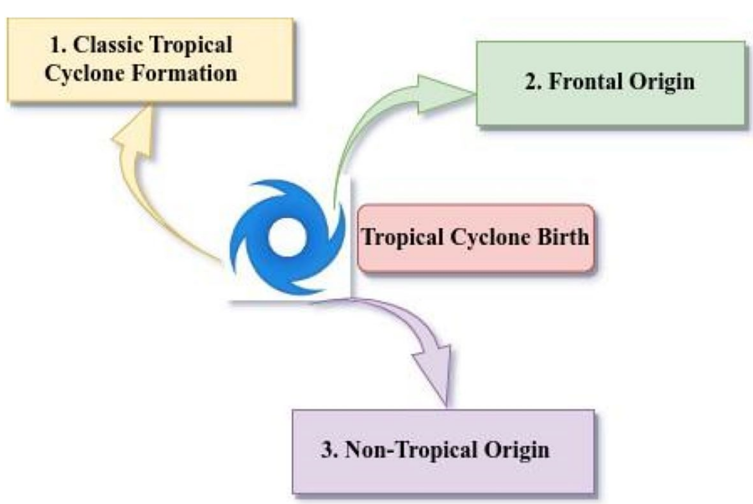

Fig. 1 Birth cycle of a cyclone

Too little heat will be accessible and too little evaporation will occur if the sea surface is too cold, which will not provide the tropical cyclone with enough fuel. If the warm surface water layer is not deep enough, the growing tropical system will alter the underlying ocean, cutting off energy supply as well. The storm's center will experience turbulence due to strong winds, and the sea surface will chill due to rain pouring from the deep convective clouds. Should the ensuing mixing cause cool water beneath the surface layer to rise to the top, the tropical system's fuel source will be eliminated.

Warm air moving vertically is insufficient to start the formation of a tropical system on its own. Further development will happen, though, if the warm, humid air enters an already-existing atmospheric disturbance. The atmospheric pressure in the center of the disturbance decreases as the rising air heats it through the release of latent heat and direct heat transfer from the sea surface. The air rises further because of the surface winds increasing in response to the dropping pressure, which also enhances heat and vapor transfer. Thus, there is a positive feedback loop between the core's warming and the increased surface winds (Werner 2010).

2.2 Intensification

A TC usually intensifies vigorously in a short period. Hence, the intensification process grabs the attention of meteorologists to predict it with acceptable precision (see Fig. 2). Typically, this rapid intensification of a TC takes place based on some external and internal causes. The external causes are described as follows.

- The recommended water temperature must be extremely warm exceed- ing 26.5 °C to a depth of about 60 m.
- The wind shear should be low (20 knots or less)

The internal condition triggered by Hot Tower, a tropical cumulonimbus cloud, causes rapid intensification of TC. Furthermore, the significance of the fact that the low-pressure zone must be located 500 km away from the equator plays a vital role in intensifying a TC (Li et al., 2023).

The atmosphere must cool down sufficiently quickly with height for a tropical cyclone to form since the storm's periphery must be colder than its core. As long as the air around it is heavier and colder, the warm, saturated air at the center of the circulation will usually continue to rise. Deep convective clouds can form because of this vertical movement. At elevations of about 5,000 m (16,000 feet), some air from the outside environment is also drawn in by the rising air in the core. This circulation will get stronger if the outside air is somewhat humid. It may evaporate some of the water droplets in the rising column if it is dry enough, making the air below it colder than the surrounding air. Strong downdrafts will arise because of this cooling, disrupting the rising motion and preventing development (Li et al., 2021).

For tropical cyclones to exhibit their distinctive quick rotation, the low-pressure center needs to be situated at least 500 km (300 miles) away from the Equator. The Coriolis force will not be strong enough to produce the required spin if the initial disturbance occurs too near to the Equator. A cyclonic rotation is created when the air being sucked into the surface low-pressure center is deflected by the Coriolis force. The ensuing circulation around the low is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

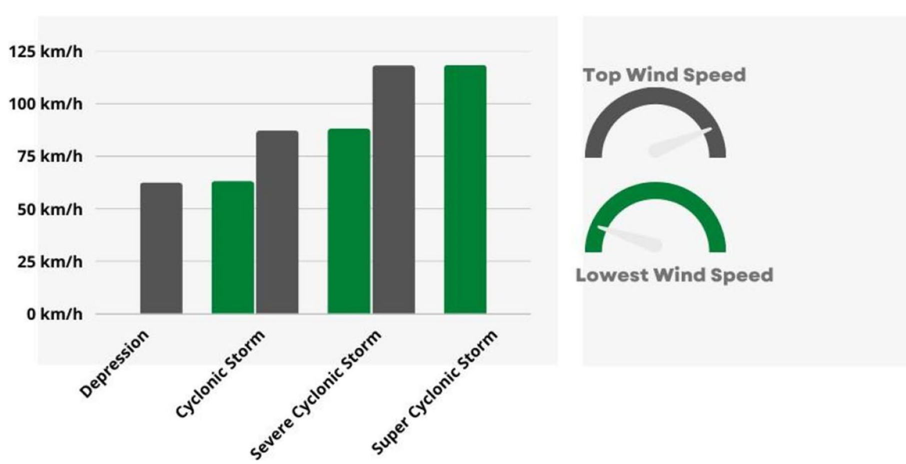

Fig. 2 Cyclone intensity

One last prerequisite for tropical cyclone intensification is minimal wind speed variation with altitude above the surface. The system's core will no longer be vertically aligned above the heated surface that supplies its energy if the winds pick up too much speed as it ascends. The above-described positive feedback loop will be inhibited when the region being warmed, and the surface low-pressure center separate. A generally slight north-to-south temperature differential is one of the tropical conditions that promote the formation of tropical cyclones. Because there isn't much of a temperature differential, wind speed doesn't change much with height (Gray 1982).

2.3 Dissipation

The dissipation phase of a TC starts when it can no longer generate sufficient energy from the warm ocean water. The demise of a TC can be formulated with cooler water alongside its movement toward land forces to lose its fuel ultimately causing the degradation of its intensity. A north-to- south-bound TC usually weakens and dissipates within a few days. These cyclones can expedite their demise by churning up deeper, cooler ocean waters. Furthermore, when a tropical cyclone traverses over land, it experiences an abrupt cessation of its energy source, resulting in a rapid loss of intensity (Ozawa and Shimokawa 2015).

When a tropical cyclone remains over the ocean but ventures into higher latitudes, a noteworthy transformation occurs, leading to its reclassification as an extratropical cyclone. This alteration is characterized by a shift in the storm's structure, including an increase in diameter and a change in shape from circular to comma- or v-shaped as its rainbands undergo reorganization. An extratropical cyclone typically exhibits higher central pressure, resulting in lower wind speeds compared to its tropical counterpart.

The process of transitioning from a tropical to an extratropical cyclone is marked by the extratropical system being fueled by a north-to-south variation in temperature. This variation contrasts with the tropical cyclone's dependence on warm ocean waters. Extratropical cyclones tend to weaken and dissipate within a few days, reflecting their reliance on a different set of atmospheric dynamics. The ultimate dissipation of these extratropical cyclones is part of the natural life cycle of these atmospheric systems (Osso´et al., 2009).

2.4 Composition of a TC

The wind field of a TC can be categorized into three parts the Eye, the Eyewall, and the Rainbands (see Fig. 3). The First one is a characteristic feature formed with a low atmospheric pressure of 960 millibars, slightly deviated from normal atmospheric pressure with a warm core temperature and a clear center. Typically, the Eye is formed with a circular region having a diameter of 40–65 km surrounded by the Eyewall.

The Eyewall, typically 15 to 30 km (10 to 20 miles) from the center of the storm is considered as the most dangerous and destructive part of a TC having the strongest winds and heaviest precipitation. Usually, The Eyewall exhibits vertical wind shear up to 5 to 10 m per second.

Rainbands can be described as a rainfall zone of cyclones, surrounding the Eye and having a spiral formation associated with clouds and precipitation. The spiral structure of Rainbands centered on the eye is considered stationary relative to a moving cyclone which is responsible for heavy torrential rain associated with the cyclone. The cycle of the TC typically has a range between 50 to 160 km, where the winds uniformly increase towards the eye of the cyclone (WaNg 2012).

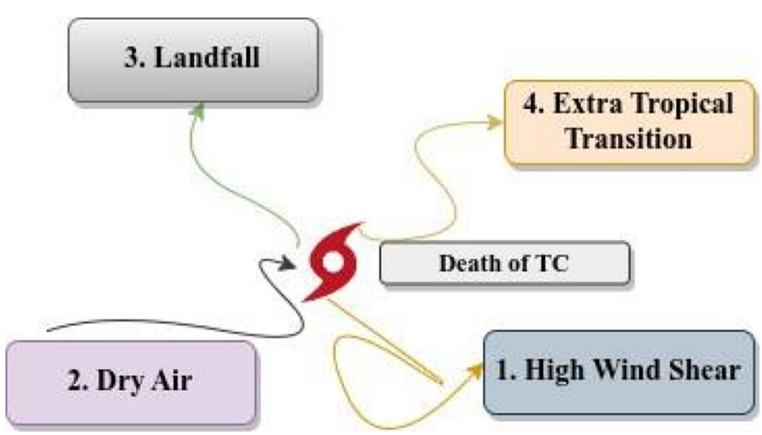

Fig. 3 Death cycle of a cyclone

3 Cyclone warning system in Bangladesh

In this section, we present a details investigation of the cyclone prediction system in Bangladesh, which includes two phases:

- Phase 1: Cyclone scenario observation system in BMD
- Phase 2: Limitation of the current system BMD

3.1 Phase 1: Cyclone scenario observation system in BMD:

Bangladesh is one of the most susceptible countries to calamities brought on by tropical storms which leads Bangladesh and fourteen of its nineteen coastal districts to be exposed to the risk of TCs (Debsarma 2009). The coastal region of Bangladesh makes up 19 districts and encompasses an area of 47,201 sq. km, or 32% of the country. The coastline region is home to 35 million people, or 29% of the total population (Mohit 2018). Bangladesh is therefore the most vulnerable region for the cyclone early warning system due to its geographic location.

Following we will describe the current cyclone monitoring system in BMD to have a clear picture of how the existing system exists.

3.1.1 Tropical cyclone warning stages

BMD uses satellite images to monitor low-pressure areas over the Bay of Bengal. They provide the first warning when a zone of low pressure intensifies and moves towards the north (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015). They categorize these warning stages into multiple groups for ease of understanding.

Cyclone alert stage This first stage gets activated at least 36 h before a predicted landfall when the speed of the rotating wind within a TC reaches 50 km/h (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015).

Cyclone warning stage At least 24 h ahead of a predicted landfall the second stage gets activated when the wind speeds settle between 51 km/h and 61 km/h (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015).

Cyclone disaster stage This stage activates 18 h before the landfall when TC exceeds its speed of 61 km/h.

Cyclone great-danger stage This stage activates 10 h before the land- fall and TC exceeds its speed of 89 km/h (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015).

3.1.2 Forecasting process of BMD

The Storm Warning Center (SWC), a specialized unit within the BMD, plays a pivotal role in collecting meteorological data and sea surface information from diverse sources such as land-based stations, radar facilities, satellites, and ocean buoys. This wealth of data serves as the foundation for the center's efforts in weather prediction and cyclone alerts (The macroeconomic consequences of disasters 2009).

Presently, BMD employs two primary methodologies for tropical cyclone (TC) forecasting: Steering and Persistence (STEEPER) and Storm Track Prediction (STP) (Economic modeling for disaster impact analysis: Past, present, & future 2007; Noy 2016). These approaches are integral to the forecasting process, utilizing sophisticated techniques to analyze atmospheric and oceanic conditions. However, it has been observed that, despite their utility, neither of these methods attains a level of accuracy deemed meaningful beyond a temporal horizon of 12 h (Economic modeling for disaster impact analysis: Past, present, & future 2007).

The acknowledgment of this limitation underscores the ongoing challenges in extending the precision of tropical cyclone forecasts over longer timeframes. As the SWC continuously refines its methodologies and incorporates advancements in meteorological science, addressing this temporal constraint remains an area of active research and development. Enhancing the accuracy of tropical cyclone forecasts beyond the 12-h window is crucial for improving preparedness and response measures in the face of these dynamic and potentially hazardous weather events.

In its current forecasting endeavors, BMD employs a multifaceted approach, incorporating a triad of forecasting techniques to enhance the accuracy and reliability of tropical cyclone predictions. These methodologies are as follows:

- Steering Airflow Determination: This technique involves a comprehensive analysis of the steering airflow, a critical factor influencing the trajectory and movement of tropical cyclones. By examining the pre- vailing atmospheric conditions and airflow patterns, BMD endeavors to predict the potential paths that a tropical cyclone may follow (Werner 2010).
- Averaging Across Historical TCs: Leveraging historical data on tropical cyclones (TCs), BMD incorporates an averaging approach. By synthesizing information from past TCs, the forecasting system seeks to identify recurring patterns, trends, and behaviors. This method harnesses the collec-

tive knowledge embedded in historical records to inform more accurate predictions for upcoming cyclones (Li et al., 2023).

- Climatology and Persistence: The integration of climatology and persistence techniques involves a meticulous examination of long-term cli- mate data and the persistence of prevailing meteorological conditions. By assessing the historical performance of atmospheric variables and their persistence over time, BMD aims to make informed predictions on behavior and intensity of tropical cyclones (Li et al., 2021).

This combination of forecasting techniques underscores the complexity of tropical cyclone prediction and highlights BMD's commitment to employing diverse and complementary methodologies. The synergy of these approaches contributes to a more comprehensive understanding of the intricate dynamics governing tropical cyclones, ultimately enhancing the precision of forecasting efforts by the Bureau.

3.1.3 Example scenario: Case study cyclone MORA

Practical knowledge and expertise are needed to predict and keep an eye on tropical cyclones (TCs), particularly when TCs are linked to an under- standing of the physics and dynamics of formation, intensity, and structural change. Knowing the distinction between developing and non-developing cy- clones is necessary to predict a cyclone. A non-developing tropical cyclone may be caused by a unidirectional upper tropospheric flow that results in vertical wind shear above the cloud cluster. It is claimed that lower tropospheric contact causes a size change and has an indirect influence on the change in intensity of a TC, whereas both upper tropospheric interaction and inner core convective heating may have a direct impact on the intensity of a TC. Moreover, a cyclone's motion usually results from the interplay of two nonlinear processes, such as the steering current and the Earth's vorticity field. In that regard, BMD used cyclone MORA, which occurred in May 2017, to test the validity of the previously described notion.

BMD detected and monitored cyclone MORA using synoptic observation along with different numerical products and satellite imagery. Over time, BMD also considered radar imagery. Cyclone MORA overall meets the criteria of a developing cyclone having a sea surface temperature of more than 26.5°, the absence of strong vertical wind shear, and an increase in vorticity over the cyclone formation area. According to BMD, numerical weather prediction (NWP) models are less capable of predicting the change in intensity, whereas approximate pieces of information on the genesis and movement of a TC could be extracted by different numerical models as well as synoptic and statistical models. An in-depth study has been undertaken by BMD to analyze and examine the various features of cyclone MORA, like genesis, intensification, movement, and landfall. Following we have listed the parameters used in cyclone MORA.

Features through Radar Image: Features observed through radar image are as follows: (i) Khepupara Doppler Weather Radar imageries, (ii) Moulvibazar Radar imageries, and (iii) Cox's Bazar Radar imageries.

Recorded Variables: The list of recorded variables is as follows: (i) Recorded Pressure (Barograph chart of different places) (ii) Recorded wind (Wind speed and direction), (iii) Recorded Maximum wind during landfall, and (iv) Recorded rainfall during landfall.

Salient features: Some of the salient features related to MORA are as follows:

(i) Maximum sustained speed (110/120 km/hr), (ii) Gusting (130 km/hr) and lowest central pressure (978 millibars). With a lifespan of 72 hours, the track length of cyclone MORA was 1086 km. Velocity flux, accumulated cyclone energy, and power dissipation index were also calculated.

Graphical products: Graphical products of observed and forecast track with a cone of uncertainty.

Dynamical features of cyclone MORA: The Weather Research and Forecasting (WRF) model products are as follows: (i) Simulated Sea level pressure (SLP), (ii) Simulated wind at 10 m and vorticity, (iii) Simulated wind speed (km/hr) at 10 m height, and (iv) Simulated 06 hourly rainfall in mm.

ECMWF model: Model products for ECMWF simulate wind and sea levels at ten meters.

4 Research gap

In this section, we will discuss the limitations of the current system which are two folds:

- Limitation of the current cyclone prediction system in BMD,
- Limitation of literature in AI-based cyclone prediction in Bangladesh

4.1 Limitation of the current cyclone prediction system in BMD

In this section, we have listed the limitations of the current cyclone fore- casting system in Bangladesh.

Data Integration Difficulties and Sporadic Data Updates: Storm sites are routinely accessible via satellite and radar imaging, and surface observations are available every 6 h; directional wind data is only attainable every 12 h. Furthermore, above the Bay of Bengal, both surface and tropospheric data are occasionally missing. Hence, on that given occasion, BMD mostly uses 12-h-old datasets in TC track forecasting. Additionally, data sets retrieved from different organizations, like the National Centers for Environmental Prediction (NCEP), are often in such a format that BMD cannot work with them because of their poor technical support and expertise.

Forecast Validations: The procedure of assessing a forecast's accuracy involves comparing it to an observation of what occurred or using a trustworthy approximation of the actual result. When we receive the result, that's when we know the forecast was accurate. Currently, BMD is unable to generate forecast verifications because they do not employ benchmark approaches such as SHIFOR and CLIPER.

Successive Cyclonic Events and Artificial Intelligence: Successive cyclonic events, which occur when several cyclones form in a short period, can have far-reaching effects that go beyond the boundaries of AI. These natural dis- asters can devastate affected areas, seriously harming crops, infrastructure, and residential buildings. These disasters' persistent high rainfall can cause severe floods that displace communities and endanger lives and livelihoods. Such cyclonic disasters frequently necessitate significant financial and humanitarian support for rehabilitation and restoration. AI can be used to improve the accuracy and timeliness of cyclone forecasting. This can help give people more time to prepare and evacuate, which can save lives. AI can also be used to develop new disaster preparedness and response strategies. For example, AI can be used to identify and map vulnerable areas and to develop evacuation plans. Additionally, AI can be used to monitor the impact of cyclones and coordinate relief efforts. Therefore, a holistic approach to disaster preparedness and response, which encompasses not just technology but also community education, infrastructure development, and effective disaster management, is essential to address the challenges posed by successive cyclonic events and to ensure the safety and resilience of vulnerable regions.

4.2 Limitation of literature in AI-based cyclone prediction in Bangladesh

To the best of our knowledge, no study has been conducted from Bangladesh's perspective using satellite photos, and there are just two credible published papers that we could find about the forecast of TC intensity using numerical models. As a result, ML and DL have a place in this sector to aid in problem-solving.

5 Literature review

The discussion of related works is in two folds. One includes the related work based on Bangladesh cyclone prediction and others on AI-based cyclone prediction techniques. Thus, this section is divided into two parts, as follows:

- Part 1: Related work on Bangladesh Cyclone Prediction
- Part 2: AI-based Cyclone Prediction System in Bangladesh

Algorithm 1. Methodology of literature review

Step 1 Identifying issues: Cyclone Early Warning Systems, Cyclone Track Forecasting, Cyclone Intensity Forecasting

Step 2: Collecting all the research work in Bangladesh Perspective.

Step 3: Categorization of all research work into three groups: i) Numerical Model Based, (ii) Satellite Imagery-Based, and (iii) Machine Learning and Deep Learning Based.

Step 4: Exploring insights of the research works and identifying recent progress on an early warning system, track, and intensity prediction.

Step 5: Exploring the research gap.

Step 6: Suggest new domain like ML/DL to improve the identifying issues and research gaps.

5.1 Part 1: Related work on Bangladesh cyclone prediction

In this section, we have presented the summarized document of the last ten years of cyclone prediction literature review in Bangladesh. We divided the whole landscape into five categories: (i) cyclone prediction; (ii) track forecasting; (iii) intensity forecasting; (iv) non-technical; and (v) miscellaneous. The quantity of papers based on these five categories is depicted in Fig. 4, and the year-based representation is shown in Fig. 5. According to the kinds of data used for the research, Fig. 6 displays the quantity of publications. Before delving into specifics, let's review some of the fundamental and practical terms covered below. Nonetheless, Algorithm 1 provides a summary of the stages involved in the literature review. First, we'll give a quick explanation of the terms used to categorize the literature.

5.1.1 Terminology

Cyclone Prediction: Bangladesh is extremely vulnerable to tropical cyclones because of its geographic location, making cyclone prediction and monitoring crucial. With a large coastline region along the Bay of Bengal, Bangladesh is a low-lying deltaic country that regularly suffers from the destructive effects of tropical storms. The nation is particularly vulnerable to cyclones because of its dense population, scarce resources, and dearth of modern infrastructure in many coastal locations. The primary concern of an automated cyclone prediction is to identify the cyclone accurately. Initially, the identifying process declares the genesis of either a developing or non-developing TC. Identifying the eye is one of the fundamental aspects of TC formation. Accurate cyclone forecasting requires the use of satellite technologies and

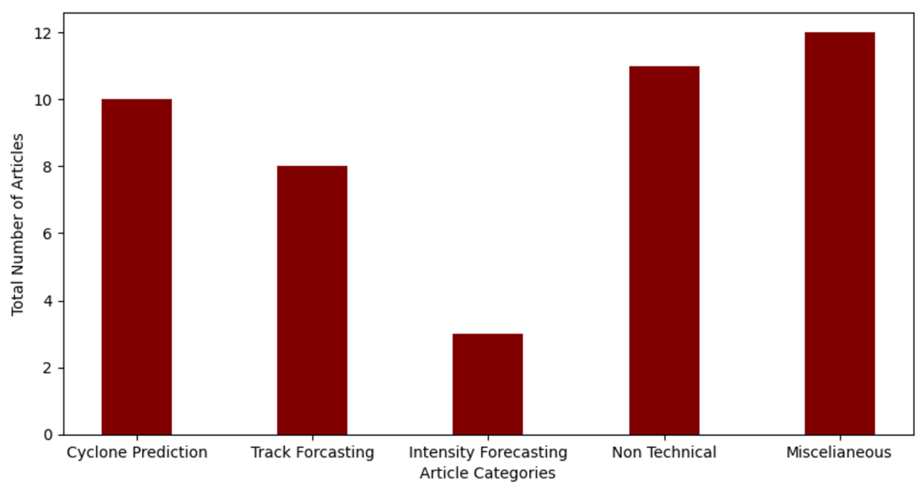

Fig. 4 Different categories of articles

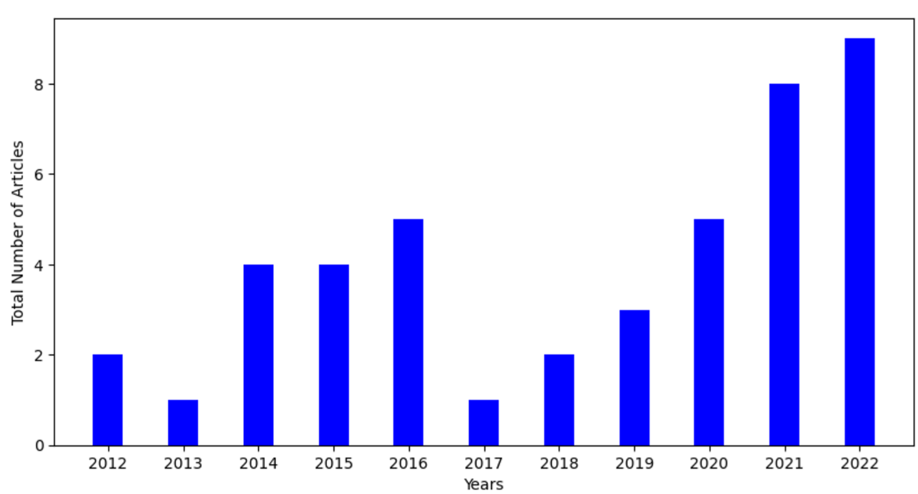

Fig. 5 Number of articles in different years

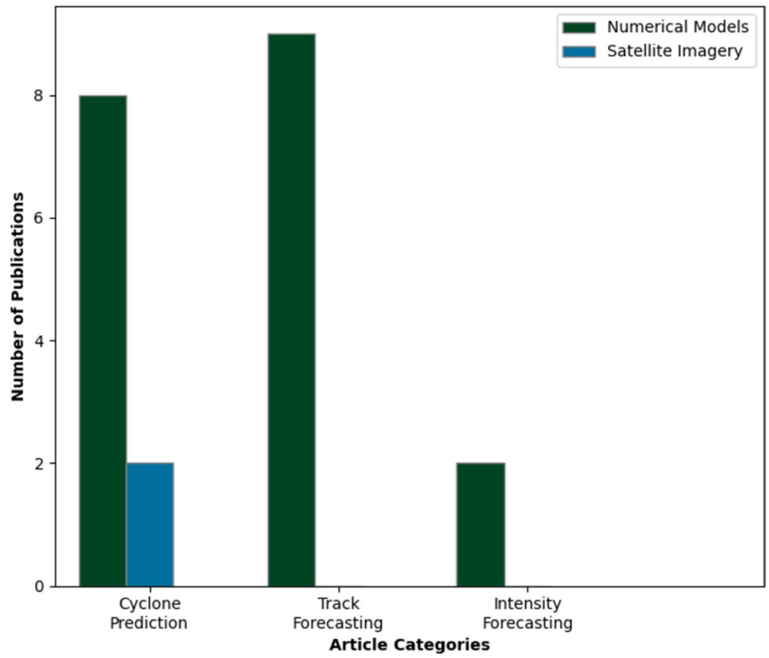

Fig. 6 Article categories based on numerical and satellite imagery

remote sensing. Meteorologists can now track the development and migration of cyclones because of these technologies, which provide real-time data on cloud formation, sea surface temperatures, and atmospheric variables. This data is essential for sending out evacuation orders and warnings promptly. Bangladesh has advanced significantly in creating and putting into place early warning systems to lessen the effects of cyclones. Cyclones are closely observed and forecasted by the Bangladesh Meteorological Depart- ment (BMD). Early warning systems are used to make sure that individuals in regions of risk are informed promptly. These methods include community- based communication systems, radio, and television.

Track Forecasting: Track forecasting includes the possible trail that a cyclone could follow with a cone of uncertainty over the next five days. Ac- curate track forecasting is essential to the proactive management of tropical cyclones, which is especially important in areas like Bangladesh which are extremely vulnerable to these types of events. Meteorologists use a wide range of high-tech instruments, such as weather radars, satellite imaging, and complex atmospheric models, to keep a close eye on the movement and position of cyclones in real-time. The cone of uncertainty, which is updated dynamically every 6 to 12 h, represents possible paths graphically while recognizing the inherent errors in cyclone track forecasting. Track forecasts are improved by determining a cyclone's position, estimating the strength of high- and low-pressure systems, and performing complex analyses of atmospheric models. Predictions become more accurate due to the interaction of numerous meteorological factors, ongoing technical developments, and international cooperation among meteorological organizations. To promote comprehensive disaster preparedness and response strategies, these forecasts must be effectively communicated to the public. This will enable communities to take well-informed action and strengthen resilience against the effects of cyclonic events.

Intensity Forecasting: Intensity forecasting is a crucial aspect of tropical cyclone prediction, particularly in regions prone to the devastating impacts of these weather phenomena. Cyclones often undergo intensification, marked by variations in wind speed and atmospheric pressure. The Saffir-Simpson Hurricane Wind Scale categorizes cyclone intensity into five levels based on wind speed, offering a standardized framework for assessing the potential impact of a storm. High sea surface temperatures and ocean heat content are pivotal factors contributing to the rapid intensification of tropical cyclones. In-depth analyses of key meteorological indicators, including increased upper-level outflow, reduced wind shear, and the relative vorticity of a tropical cyclone, form the foundation for reliable intensity forecasting. By scrutinizing these factors, meteorologists can more accurately predict the evolution of a cyclone's strength, providing essential information for risk assessment, disaster preparedness, and timely response efforts in vulnerable coastal regions.

Non-Technical Paper. Non-technical papers on cyclone prediction in Bangladesh offer valuable insights into broader aspects such as disaster management, societal responses, and the human experience in facing the recurring threat of cyclones.

Miscellaneous. Miscellaneous refers to a group of various, usually unrelated items. The paper that did not fit into any of the categories has been included in this section.

5.1.2 Literature on cyclone prediction

Tropical cyclone prediction is mainly related to the prediction of its genesis which refers to the development of a cyclone in the atmosphere (Debsarma 2009). BMD is the only organization in Bangladesh that is responsible for identifying and predicting TC initiation. They have the authority to forecast and maintain the warning system that includes information like the position of the storm center, direction of movement, maximum wind speed, affected areas, the height of the tidal surge, etc.

There have been several pieces of research on cyclones in Bangladesh. Akter and Tsuboki (Mohit 2018) conducted a numerical simulation of the outer band of cyclone 'Sidr', one of the strongest cyclones in the Bay of Bengal. They used the Cloud Resolving Storm Simulator (CReSS) model, which is a three- dimensional, non-hydrostatic, and compressible cloud-resolving model, for the simulation. The dataset was collected from different sources, i.e., BMD, Japan Meteorological Agency (JMA), etc.

Tasnim et al. (Economic modeling for disaster impact analysis: Past, present, & future 2007) also used DL and ML to address the current issue of storm surge due to'Sidr', but they used a coupled meteorology-wave-coastal ocean-tide model, an improved version of the OSIS model. The WRF model is the main component of the OSIS model. The model provided good results concerning the observations of the Indian Meteorological Department (IMD), and finally, the model was verified by comparing the findings of Shibayama et al. (Impact of flood disasters in Bangladesh: A multi-sector regional anal- ysis. xxxx). Mannan and Habib (Chowdhury 1993) used a WRF model and simulated cyclone 'Aila', which struck the North Indian Ocean in 2009. The model was a combination of the Kain-Fritsch cumulus parameterization scheme, Ferrier, Kessler, Lin, et al., WRF Single-Moment 3 Class, and WRF Single-Moment 5 Class microphysics schemes. They searched for parameters based on three main factors: vorticity, vertical velocity, and vertical wind shears, and com- pared the results with IMD and Joint Typhoon Warning Center (JTWC) archived data. A parametric Markov Renewal Process (MRP) model was proposed by Asaduzzaman and Latif (The macroeconomic consequences of disasters 2009) for predicting TCs in Bangladesh. They assumed that the sequence of cyclones builds the Markov chain and that sojourn times follow the Weibull distribution. The dataset was collected from the Global Tropical Cyclone Climatic Atlas (GTCCA) and the Center for Research on the Epidemiology of Disasters (CRED). They used the maximum likelihood method for estimation and compared the results with the Poisson Process and the Marked Poisson Process. Rayhun et al. (Noy 2016) used the WRF-ARW model for the simulation of the tare structure, track, and landfall of cyclone Bijli. The model studied parameters like minimum sea level pressure, maximum wind speed, convective available potential energy, and relative vorticity, and it was able to predict tracks, curvature, areas, and time of landfall even in advance of 96 h.

Hossain et al. (Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015) analyzed the effect of initial condition (IC) and horizontal resolution (HR) on TC predictions and found that reduced lead time and higher resolution are more appropriate for the simulation for proper TC forecasting. They achieved the result by conducting a simulation of tropical cyclone'Amphan' using the WRF-ARW model. Ahsan et al. (Khan et al., 2010) conducted a choice experiment (CE) among the coastal households in Khulna, Satkhira, and Barguna regarding their willingness to pay (WTP) for a better warning system for TC, as the existing one has many challenges. They chose the' stated preference' approach, which is widely used for the valuation of environmental goods and services, and CE is a branch of it. The study concluded that the coastal households that are at risk of cyclones were ready to pay for the improved warning service.

A couple of studies have also been conducted using satellite imagery. Begum et al. (MWR (Ministry of Water Resources) 2005) observed the cyclones from satellite images to understand and identify the formation, movement, intensity, and track of cyclones. They used the Vimsat, Gmsoft, and DVorak algorithms for the observation and analysis of satellite data, and the dataset used was collected from the SPARRSO ground station from different satellites. Hoque et al. (Ahmad 2019) proposed an object- based image analysis for evaluating the impacts of TCs in Bangladesh. The pre- and post-cyclone satellite images of 'Sidr' were used for testing their approach. They were optimistic that their approach could be used for further disaster management in similar types of calamities.

5.1.3 Literature on track forecasting

Forecasting the path of Tcs includes making predictions about their movement every 6 to 12 h for five days

(Debsarma 2009). It is very important to predict the path of tropical cyclones to minimize the damage. As 32% of Bangladesh's land is made up of the coastline zone, which spans an area of 47,201 square km and the population of the coastline region is about 35 million people which is 29% of the total population (Debsarma 2009); Bangladesh needs to trace any cyclone which is formed in the Bay of Bangle to rescue its coastal population as well as to reduce the damages. For predicting a cyclone's path, we usually use two types of data; the first one is numerical data and the second one is satellite images. From Bangladesh's perspective in most of the cases, we use numerical data to trace a cyclone. Mallik et al. (Mohit 2018) had used WRF and an MRI model to trace the cyclone Viyaru which formed over the Southern Bay of Bengal from 11–16 May 2013. They rather accurately anticipated the paths, re-curvature, regions, and time of landfall of the chosen tropical storm Viyaru.

The MRI model also predicted storm surges and the highest tide. Hussain et al. (Chowdhury 1993) researched the effects of cyclone track parameters, such as cyclone translation speed, cyclone path, and cyclone landfall crossing angle, in com- bination with tidal phase shift, at the Bay of Bengal along the Bangladesh coast. For the research, a storm surge model and a two-dimensional hydrodynamic model (2DH) in the horizontal direction were used. The final finding of their research is that coastal crossing angles are the smallest when surge durations are the shortest along both coasts. Ali et al. (The macroeconomic consequences of disasters 2009) conducted an- other study that aims to make a comparative result (surge height of cyclone) analysis between the India Institute of Technology-Delhi (IIT-D) storm surge model and the Japan Meteorological Agency (JMA) storm surge model. They used simulated data of Aila from the WRF model and estimated data from IMD as input and output results, compared with the available recorded data of surge height for this cyclone. Islam et al. (The macroeconomic consequences of disasters 2009), where they have successfully predicted the probable areas of the selected tropical cyclones with high accuracy. Table 1 present a summarization of the reviewed paper.

5.1.4 Literature on intensity forecasting

Cyclone intensity is measured by the wind speed of the cyclone, followed by the devastating cyclone, which can be measured through the intensity of that cyclone. Hence, it's very crucial to forecast the intensity of a cyclone to reduce the damage.

Saifullah et al. (Debsarma 2009) conducted research where they predicted the minimum central pressure, maximum wind speed, and track of TC Roanu using the WRF model. The JMA-developed MRI storm surge model is used to predict cyclone-induced storm surge for TC Roanu, at the same time. The simulated data from the WRF model and the observed data from the IMD are used to create the input files for this parametric model. The outcomes are compared to the available documented data on the cyclone's surge height. This study's success can be attributed to the fact that the simulated surge heights are in reasonable agreement with the storm surge data that is currently available. Nasher et al. (Debsarma 2009) analyzed the cyclone tracks from 1877 to 2020 to detect the spatial and temporal intensity. They collected the cyclone tracks from previously published works. To identify monthly and seasonal fluctuations in cyclone intensity and spatial distribution, a total of 126 cyclone tracks were examined and from their study, they found the Bangladesh coast had become less vulnerable to strong cyclones.

5.1.5 Non-technical paper

In this section, we have summarized the paper, which is based on geographical information rather than the technical background of any forecasting model. Table 2 and Table 3 show the summarized information.

Table 1 Used model in cyclone prediction

Reference	Year	Model	Dataset
Sarwar & Sweden 2005)	2012	(DRI)	EM-DAT: The OFDA/CRED
Akhand 2003)	2013	None	None
ADRC 2005)	2016	None	None
Debsarma 1999)	2016	None	(BMD), (BDG), (IFRC), (RCS)
Debsarma 2001)	2016	(DEM)	(BMD), (USGS)
System and for Cyclone and Disaster Message for Public (Original in Bengali) 2009)	2020	(INFORM) Model	None
Prepared- & ness Plan for Cyclone 2013)	2020	None	None
Klein 2008)	2021	ENSO Index	BMD, WDB, Bureau of Meteorology, Australia

Table 2 Non-technical model

Reference	Year	Model
Sarwar & Sweden 2005)	2012	Fuzzy, Neural Net
Akhand 2003)	2014	Delft3D
ADRC 2005)	2019	MOLs
Debsarma 2001)	2019	Delft3D-Flow
System and for Cyclone and Disaster Message for Public (Original in Bengali) 2009)	2021	Statistical
Prepared- & ness Plan for Cyclone 2013)	2022	Delft3D
Klein 2008)	2022	GrADS
Klein 2008)	2022	2D Shallow Water Equation
Klein 2008)	2022	Synthetic cyclone modeling
Klein 2008)	2022	ERDAS, ArcGIS

5.1.6 Miscellaneous

In this category of papers (see Table 4) on cyclone prediction in Bangladesh, there are diverse topics that touch upon unique aspects of cyclone research, offering a broad perspective on the subject. These papers cover interdisciplinary approaches, regional nuances, or specific case studies (Subhani & Ahmad 2019). Explores the financial repercussions of cyclones on the country's economy, shedding light on the long-term consequences. Another paper delves into examining the local knowledge, perceptions, and practices surrounding cyclone forecasts and response strategies [36].

5.2 Part 2: AI-based cyclone prediction system in Bangladesh

This section contains the study that uses an AI-based model and the Bangladeshi dataset. Take note that there aren't many papers available from this perspective.

5.2.1 Literature on machine learning in cyclone prediction

Cyclone prediction, tracking, and intensity forecasting are complex systems where accurate forecasting is highly dependent on different numerical variables and data. Depending on the numerical and statistical model intensity, forecasting encounters many errors. In this study, we will be discussing the research work done from Bangladesh's perspective. ML is a subdivision of the core technology of AI which explores the potential values of data by feeding it into computers and letting them infer rules from it to improve their performances (Mohit 2018). ML models can be partitioned as supervised learning, unsupervised learning, and reinforcement learning, which obtain experience through interaction with the environment (Chowdhury 1993). The ML model has substantial advantages in data processing and image recognition, which ultimately helps to work on satellite images to predict the track and intensity of TCs.

Several ML algorithms have been used, like Convolution Neural Network (CNN), Support Vector Machines (SVM), K-Nearest Neighbor (KNN), Ran- dom Forest (RF), Gradient Boosting (XGBoost), and Artificial Neural Net- work (ANN), to detect cyclones. You Only Look Once (YOLO) is an algorithm that has been used for the eye localization of cyclones. However, in the past decade, track forecast errors have, for instance, been reduced by 66% both in the North Pacific and Atlantic, whereas intensity forecasts have improved by only one-third to one-half of this rate (Debsarma 2009). As intensity forecasting is a complex system, non-linear models like ML or DL can be addressed to decrease the error rate of intensity forecasting as well as increase the accuracy rate and performance of track forecasting (Debsarma 2009).

In this study, we shall be reviewing the current applications of ML methods in theforecasting of TC, track and intensity from a Bangladesh perspective. From the graph, we can realize that not a chunk of work has been done using ML models. Nevertheless, we find M. Hussain et al. (The macroeconomic consequences of disasters 2009) introduced supervised machine learning techniques to assess tropical cyclones in BOB. In this study, they found latent heat release from the Bay of Bengal (BOB) is one of the reasons that extreme weather events like TCs, heavy rainfall, floods, and thunderstorms cause extreme damage to the agriculture industries and human lives. Using the NWP model in this scenario is time-consuming and concerns computational resources. Therefore, the authors aimed to estimate the predictability and accuracy of supervised ML for TCs by assessing air temperature at 2 m (AT) and Sea Surface Temperature (SST). This research is divided into two parts: a) Data normalization via Linear regression (LR) and Multi-Linear Regression (MLR) and b) Supervised ML techniques application in Matlab 2018b. The dataset provided by BMD and ERA5 is split into the train (80%) and test (20%) to feed the machine learning model Coarse Decision Tree (CDT). The result suggests that Chattagram, Barisal, and Khulna divisions have a stronger correlation to SST in BOB with $R = 0.919$, 0.850, and 0.846 respectively. The outcome of this research work indicates that SST prediction is possible with 98% accuracy based on coastal stations. The proposed ML model can validate prediction using observed AT to forecast monthly SST with 85% accuracy for monthly time series data. The future work of this project is defined as further assessment of various categories of tropical cyclones and prediction of their intensity based on SSTs.

Table 3 Miscellaneous papers

Reference	Year	Model	Dataset
Debsarma 2009)	2014	Fuzzy, Neural Net	An improving cyclone warning proposed system for BMD. So, no dataset had used
Debsarma 2009)	2019	Two-dimensional coastal modeling using Delft3D	Projected changes of inundation of cyclonic storms in the Ganges–Brahmaputra–Meghna delta of Bangladesh due to SLR by 2100 | SpringerLink
Mohit 2018)	2019	method of lines (MOLs) with higher order central difference approximation method coupled with the classical fourth order Runge–Kutta (RK(4,4)) method	Mathematical analysis. So no dataset needed
Chowdhury 1993)	2019	A coupled model comprises Delft3D-Flow	GDACS (2017)
The macroeconomic consequences of disasters 2009)	2021	Statistical (Used Satellite Imagery)	Satellite images were collected from USGS for the years 1988, 1991, 1997, 2007, 2009, 2019
Noy 2016)	2022	Delft3D	FINN map data developed from the land survey by Bangladesh Inland Water Transport Authority (BIWTA), ocean bathymetry data of the Bay of Bengal are taken from the open-access 30-arcsecond General Bathymetric Chart of the Oceans (GEBCO) data (Weatherall et al., 2015), the major rivers is taken from the measured cross-sectional data from Bangladesh Water Development Board (BWDB) and the ESPA Deltas project (ESPA, 2012)
Economic modeling for disaster impact analysis: Past, present, & future 2007)	2022	GrADS	Data Access—OISST | National Centers for Environmental Information (NCEI) formerly known as National Climatic Data Center (NCDC); access date: June 19, 2021
Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015)	2022	A two dimensional vertically integrated shallow water equation in the Cartesian coordinate model	Dataset from Bangladesh Meteorological Department (BMD)
Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015)	2022	synthetic cyclone modeling (Category 4)	The satellite data were obtained from Earth explorer site (http://earthexplorer.usgs.gov/) and Google images from Google Earth
Khan et al., 2010)	2022	ERDAS, ArcGIS	International best track archive for climate stewardship (IBTrACS)

Table 4 Reviewed papers

Ind	Year	Dataset	Method	Simulated Software	Findings
Debsarma 2009)	2011	NCEP for providing the global analysis and forecast fields Precipitation data provided by NASA The track	The model uses The techniques as follows: A Eulerian mass dynamical core with terrain- following hybrid sigma-pressure vertical coordinates with Arakawa C-grid staggering. The model uses the	WRF 2.2.1 (Weather Research and Forecast model) Convective parameterization scheme The planetary boundary layer schemes of Yonsei University (YSU)	In this proposed system WRF model is used to simulate four severe cyclones occurred over Bay of Bengal by comparing the parameter such as cyclone track, intensity, and landfall time with available observations. The cyclone simulations show that the model could predict the cyclone track, intensity in terms of central pressure, maximum sustained winds, and precipitation reasonably well The model well predicted the intensity of central pressure and wind except for cyclone Sidr. This suggested that the model performance is heavily dependent on initial errors. The large error of wind
Debsarma 2009)	2012	GFS analysis and forecasts and TRMM rainfall data		ARW version 3.2 mesoscale model KF convection LIN microphysics YSU PBL scheme	
Mohit 2018)	2012	NCEP–NCA R BMD	The model's basic equations were solved in the terrain- following coordinates with	The numerical model CReSS The Grid Analysis and Display System software (GrADS) was used	
Chowdhury 1993)	2012	The data used here is based on some drastic assumption Total			It is observed that there is a good relation between cyclone risk and development level of the coastal areas of Bangladesh
Noy 2016)	2014	The hourly data obtained from	Algorithm. The FY2D satellite images were enhanced	Gmsoft	events thus is useful to warn people much ahead of time about the occurrence of the weather calamities like cyclone
Economic modeling for disaster impact analysis: Past, present, & future 2007)	2014	N/A (Numerical Dataset) Wind -	Neuro – Fuzzy Algorithm used: Fuzzifier, Neuronet	N/A	By taking only parameter "wind speed" and divided the wind speed into nine categories the proposed system provides 84% accuracy
Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015)	2014			WRF Single- Moment 3 NCEP/FNL Ferrier Kessler	
Impact of flood disasters in Bangladesh: A multi-sector regional analysis 2015)	2014	(GTCCA) CRED	Markov model		

5.2.2 Literature on deep learning in cyclone prediction

The availability of data sets allowed researchers to introduce deep learning into the field of remote sensing. DL algorithms show tremendous performance in cyclone prediction if it is taken into consideration to run the algorithm on a graphical processor unit (GPU). Recent technology is not only limited to GPUs but also uses a tensor processing unit (TPU), which is faster than GPUs for running DL algorithms. The DL framework is used for the classification of satellite images and the selection of required features or parameters from them to feed the algorithm. To clear up the misconception, "deep" in deep learning is not studying an algorithm deeply; rather, it is defined using several numbers of layers and hidden layers in its framework, unlike machine learning algorithms.

In this study, we will be discussing the research work done from Bangladesh's perspective briefly. N. Haque et al. (Noy 2016) describe DL methods in terms of their work on cyclone detection and cyclone eye localization. Their methodology of work can be divided into three parts. a) Image pre-processing; b) Cyclone detection; and c) Cyclone eye localization Data preprocessing is done using grayscale, filtering, resizing, thresholding, and interpolation so that clean data takes less computational resources and time. Different algorithms used to predict cyclones provide a result of 95.15% accuracy for CNN, 94.17% accuracy for SVM, 86.73% accuracy for KNN, and 93.20% accuracy for RF. Based on cross-validation, CNN, SVM, and ANN provide accuracy of 98.29%, 99.84%, and 96.51%, respectively, for K-fold. The authors in this work also provide the insight to detect multiple eyes formed in an image. However, there is always room to improve this work by enriching the data for forecasting and tracking.

6 Research gap

In this section, we will discuss the limitations of the current system which are two folds:

- Limitation of the current cyclone prediction system in BMD,
- Limitation of literature in AI-based cyclone prediction in Bangladesh

6.1 Limitation of the current cyclone prediction system in BMD

- *Data Integration Difficulties and Sporadic Data Updates:* Storm sites are routinely accessible via satellite and radar imaging, and surface observations are available every 6 h; directional wind data is only attainable every 12 h. Furthermore, above the Bay of Bengal, both surface and tropospheric data are occasionally missing. Hence, on that given occasion, BMD mostly uses 12-h-old datasets in TC track forecasting. Additionally, data sets retrieved from different organizations, like the National Centers for Environ- mental Prediction (NCEP), are often in such a format that BMD cannot work with them because of their poor technical support and expertise.
- *Forecast Validations:* The procedure of assessing a forecast's accuracy involves comparing it to an observation of what occurred or using a trustworthy approximation of the actual result. When we receive the result, that's when we know the forecast was accurate. Currently, BMD is unable to generate forecast verifications because they do not employ benchmark approaches such as SHIFOR and CLIPER.
- *Successive Cyclonic Events and Artificial Intelligence:* Successive cyclonic events, which occur when several cyclones form in a short period, can have far-reaching effects that go beyond the boundaries of AI. These natural dis- asters can devastate affected areas, seriously harming crops, infrastructure, and residential buildings. These disasters' persistent high rainfall can cause severe floods that displace communities and endanger lives and livelihoods. Such cyclonic disasters frequently necessitate significant financial and humanitarian support for rehabilitation and restoration. AI can be used to improve the accuracy and timeliness of cyclone forecasting. This can help give people more time to prepare and evacuate, which can save lives. AI can also be used to develop new disaster preparedness and response strategies. For example, AI can be used to identify and map vulnerable areas and to develop evacuation plans. Additionally, AI can be used to monitor the impact of cyclones and coordinate relief efforts. Therefore, a holistic approach to disaster preparedness and response, which encompasses not just technology but also community education, infrastructure development, and effective disaster management, is essential to address the challenges posed by successive cyclonic events and to ensure the safety and resilience of vulnerable regions.

6.2 Limitation of literature in AI-based cyclone prediction in Bangladesh

To the best of our knowledge, no study has been conducted from Bangladesh's perspective using satellite photos, and there are just two credible published papers that we could find about the forecast of TC intensity using numerical models. As a result, ML and DL have a place in this sector to aid in problem-solving.

7 Proposed AI-based model to address the current issue

In this section, we presented an AI-based cyclone prediction system based on the research gaps, which can be implemented by BMD in any country that is prone to cyclones. Before going into details, Fig. 7 describes the overall workflow of the paper.

Cyclone forecasting techniques using machine learning: A proposed AI-based cyclone. Prediction System involves several fundamental machine learning (ML) steps. First and foremost, gathering historical cyclone data and pertinent meteorological aspects is essential. After that, data preprocessing includes preparing the data for model training by cleaning, transforming, and normalizing it. The identification of significant variables is mostly de- pendent on feature engineering and selection. The selected machine learning algorithm, typically a supervised learning technique—is trained using the al- ready prepared dataset. The model is validated and fine-tuned after training to maximize performance. After that, the finished model is put to use for real-time cyclone prediction, continuously improving its efficacy and accuracy by learning from incoming data.

Fig. 7 Workflow diagram of the paper

In Fig. 8, we demonstrate the cyclone forecasting techniques using machine learning.

7.1 GAN-based data augmentation

One possible solution to the issue might be to expose the system to synthetic data using DL and ML. In this connection, we propose a Generative Adversarial Network (GAN) which is a technique that uses two neural networks to produce fictitious yet realistic data points that we may subsequently use to feed our ML models since forecasting cyclonic events requires many data points.

Working Procedure of a GAN: As previously stated, GAN includes two neural networks. A discriminator and a generator. As the name implies, the generator creates fictitious data to trick the discriminator, and the discriminator's goal is to detect or separate fake data from real data. The real data samples and fake data points generated from the Generator are sent to the Discriminator. The Discriminator then determines whether the labeled data is fake or real on a scale of 0 to 1, where 0 represents fake data and 1 represents authentic data. The generator generates actual data samples and fake data points, which are sent to the Discriminator. The basic tenets of GAN in our proposed methods will be covered in the parts that follow. In Fig. 9, a general diagram of the GAN model has been included.

7.2 Machine learning in forecast validations:

ML is a field of AI that trains computers to think like humans by learning from previous experiences and improving through definite feedback without explicit programming. It operates by analyzing data and discovering patterns with little human participation. ML models have certain essential characteristics that might be quite valuable in the cyclone monitoring and forecasting validation process.

Validation for cyclone forecasting is important because it prevents the model from becoming a major concern for the forecasters. Accurate forecasting often depends on validating a model properly which could be achieved by acquiring the right and correct data sets. Security is a crucial component that prevents data leakage using ML models since data is too significant in many ways, especially when it is private and sensitive. Reliability enables us to recognize the strengths and weaknesses of an ML model, allowing us to decrease forecast errors. ML model and data set with bias built decrease the performance of forecast. Finding inappropriate bias and fixing the bias is a major issue for forecast validation. Concept drift occurs when an ML model is allowed to deteriorate and what it predicts differs from what it was designed to predict. In Fig. 10, we have demonstrated the procedure for forecast validation.

7.3 Successive cyclonic events and artificial intelligence

Tropical cyclones are one of the most damaging natural catastrophes on Earth. Along with severe wind speed, it brings torrential rain, and storm surge inundation in coastal areas. Torrential rains are introduced by large and slow-moving tropical cyclones.

Torrential Rain: Determining the slope stability of hill tracts using an ML model to identify landslides in a cyclonic event would be very useful. Many times we observe that cyclone-induced showers cause landslides because when a TC passes through the affected areas, it acts differently due to the intense precipitation generated by the cyclone. Two main concerns describe landslides during a cyclone because of slope failure. Rainfall accumulation from exposed bedrock slopes, resulting in excess overland flow for concave topography; and wind and surplus overland flow on the relatively convex or flat higher slopes.

A slope is either vulnerable or stable which can be determined by the FOS value which acts as a safety factor. The geometric features that we could use to feed our ML models are slope height, slope angle, bulk density,

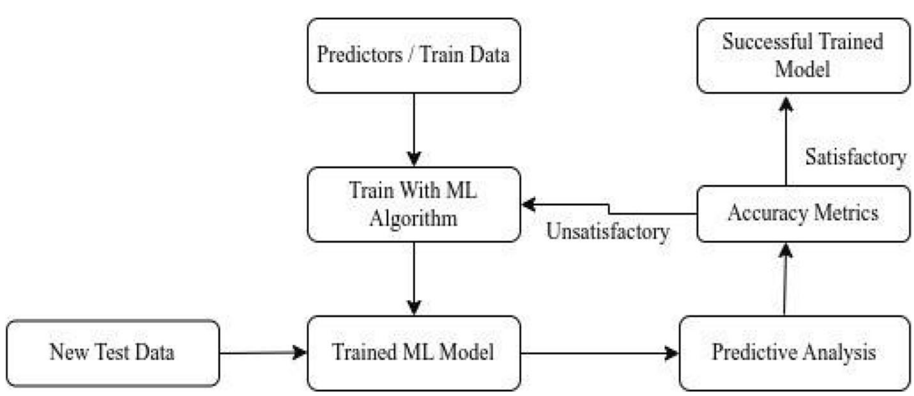

Fig. 8 General diagram of machine learning model

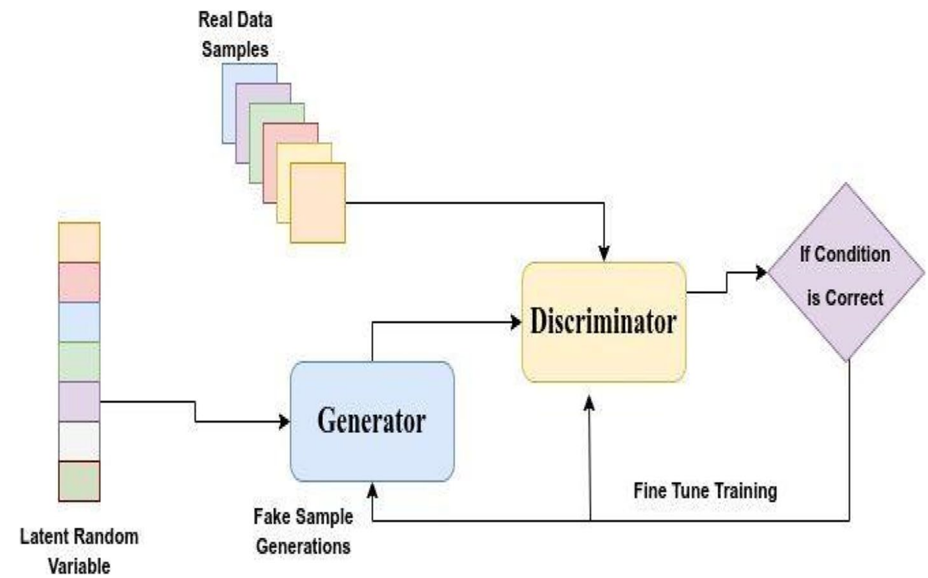

Fig. 9 General diagram of GAN model

cohesion, and internal friction angle. We set the FOS value as our target. We define the threshold value for FOS as 1.05. If we find our generated FOS value by the ML model is greater than our defined threshold value of 1.05 then we could conclude that the slope is stable. The threshold value can be determined through the intensity and the duration curve of the storms.

Storm Surge Inundation: Bangladesh's southern boundary is along the BOB. The mainland is around 24,800 square miles in size and includes a 710 km- long coastline. The BOB has intricate ocean currents since it is narrow in the north, is bordered by coasts in three directions (east, north, and west), and has many rivers flowing through it. Tidal waves often bring saline water and have minimal contact with inland areas. However, a cyclonic storm surge presents a whole new set of circumstances. The phrases tidal bore, bore, tidal-surge, cyclonic-surge, and storm-surge are sometimes used interchangeably in Bangladesh. Cyclonic surge refers to the large surge of saline water that travels with a cyclone and flows like an oncoming wave. The cyclonic surge may be caused by two distinct marine disturbances connected to storms. The cyclonic wave is the first kind. This happens at the calm storm's center. A significant amount of water at and around the storm center is pushed up collectively, frequently to a height of 6 m, and moves with the storm as a wind-driven storm surge. The volume of water that comes into touch with the ground during a storm surge might pose a danger to ecological stability, regional ecology, food security, and long-term agricultural growth. This problem can be addressed as a binary classification problem using several ML algorithms (SVM, DT, RF) to identify the salt-affected irrigated crop field affected by saline water. Several DL models can also be useful to detect saline water fields using satellite image data.

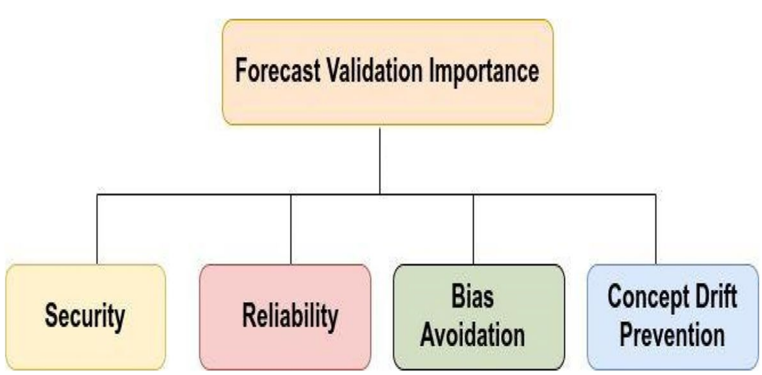

Fig. 10 General diagram of forecast validation

7.4 Early warning system using ANN and hydrological sensors

People living in coastal areas are affected most when a cyclone hits that region. The coastal area inundated because of storm surge can be monitored in real-time using ANN and Recurrent Neural Network (RNN). Using AI in this sector to get a clear picture of incoming floods can act as an early warning system. ANN is a core part of AI that processes information as the human brain does. Additionally, it has self-learning capabilities and can accomplish some complicated tasks that would be impossible for the human being. It is possible to get the expected outcome in an early warning system using ANN and hydrological sensors for storm surge prediction.

7.5 4IR in cyclone management in Bangladesh

As the world is not static, it evolves as time passes. This era is passing through the 4th Industrial Revolution which is reshaping our world in many aspects like economies, businesses, and industries (Klein & Calderwood 1991). Developed countries like the USA, China, Japan, and others implementing robotics, and AI robot technology are used to forecast cutting and improve productivity. Starting from bullet trains to AI-based employees to cut the cost short and many more. Internet of Things (IoT) applications such as houses with smart technology, and autonomous vehicles are making life easier. Furthermore, the uses of augmented reality and virtual reality are spread over time. Eventually, this handful of technologies can be used in different weather management tasks such as cyclone prediction and tracking, solar flare detection, identifying radioactive substances in the air, etc.

Although adverse weather conditions like TC cannot be averted and recovery can be acquired by using technology, it can be used to prevent loss of properties and lives on such technology as the Global High-Resolution Atmospheric Forecasting System (IBM GRAF) developed by IBM that helps democratize weather forecasts accurately. IBM claims their system could predict weather conditions up to 12 h in advance without having detailed data access. They also added that the other global weather models cover 10- 15 km squared and are updated every 6 to 12 h whereas they cover a 3 square km squared area and get updated hourly. The handful use of technologies in cyclone management can open up a new era that could bring the revolution in this domain and the inception could be just starting with ML and DL that Bangladesh might follow in the upcoming days.

Bangladesh has shown commendable technological advancement for the last several years, but it is yet to reach its target of achieving the full advantage of using, especially in the field of weather forecasting systems. Bangladesh needs to focus on implementing and using these innovative concepts in its existing cyclone prediction systems. Moreover, a center database is required for a weather-related data repository which will allow big data analysis. This will boost the efforts of concerned people who have enthusiastic minds to contribute to this domain.

8 Conclusion and discussion

Being a geographically vulnerable country, Bangladesh faces the severity of many disasters on different occasions. Among those, the severity of TC has an immense impact on the living beings and livelihoods of the people in this region. Hence, monitoring and tracking a TC accurately has become a serious issue in this context. As this study is constrained to Bangladesh perspective, we found 47 research papers on cyclone monitoring and prediction related to the region. Most of the research work is done using a numerical model instead of an ML or DL model, which ultimately paved the path to exploring the use of ML and DL in this domain. In the future, we would like to use both numerical and satellite image data to predict complicated tasks like the intensity of a TC and the localization of the eye of a cyclone using ML and DL.

A tropical cyclone is a major concern for people living in coastal areas of any cyclonic basin in the world. In this context, Bangladesh cannot be ruled out as a safe zone for cyclonic activities since this deltaic land is in the vicinity of the BOB. Without proper precautions and measurements, our entire coastline could be affected by an intense cyclone if it randomly changes course, as this cyclonic event is considered a nonlinear system. Therefore, we feel the need for a system that could predict and monitor any cyclonic events optimally. This research work finds the lack of a proper model that could predict a TC optimally in terms of track and intensity forecasting since all the prevailing numerical models have some limitations. Hence, we proposed using ML and DL models in this domain to understand the structure, formation, and dynamics of a TC, as ML and DL can identify the important features from a huge chunk of a data set automatically, which could contribute to identifying the bottleneck of the prevailing numerical models minutely. As a new domain to work on, it could be both challenging and full of opportunities to implement this model alongside numerical models. Since any cyclonic event is complex, and many factors led to further comprehensive studies in this field.

Code availability
Not applicable.

Authors' contributions
SR and NS formulated research questions, conducted the search, and finalized the selection of articles for review; performed data extraction; performed data synthesis and analysis; SR and MR prepared the initial draft; and MBM revised and finalized the article; NS and MR supervised the whole process. All authors reviewed and approved the manuscript.

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Declarations

Ethics approval and consent to participate
There are no studies by any of the authors in this article that used humans or animals as subject.

Competing interests
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